Standardized Acceleration Processing for Airport Pavement Roughness Evaluation

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Outline

1. International Standards Organization (ISO) old vibration limit criteria.
2. Aircraft center of gravity (CG) and cockpit peak accelerations with different bandwidths.
3. New ISO acceleration weighting functions and index functions.
4. ProFAA and ProView used for comparison between measured and simulated aircraft responses.

Mechanical Model of the Human Body

Resonant Frequencies

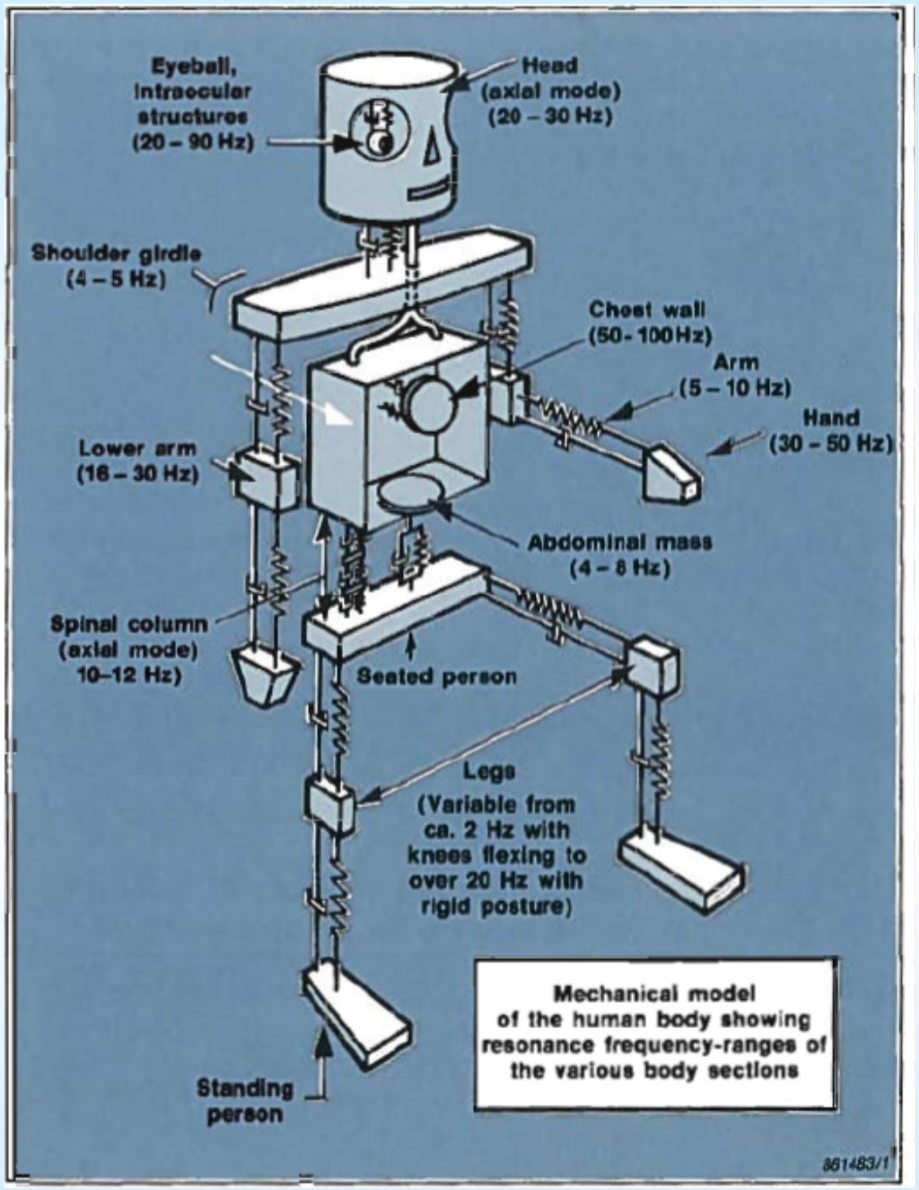
Head: 20 – 30 Hz

Arm: 5 – 10 Hz

Abdominal Mass: 4 – 8 Hz

Eyeball: 20 – 90 Hz

Spinal Column: 10 – 12 Hz

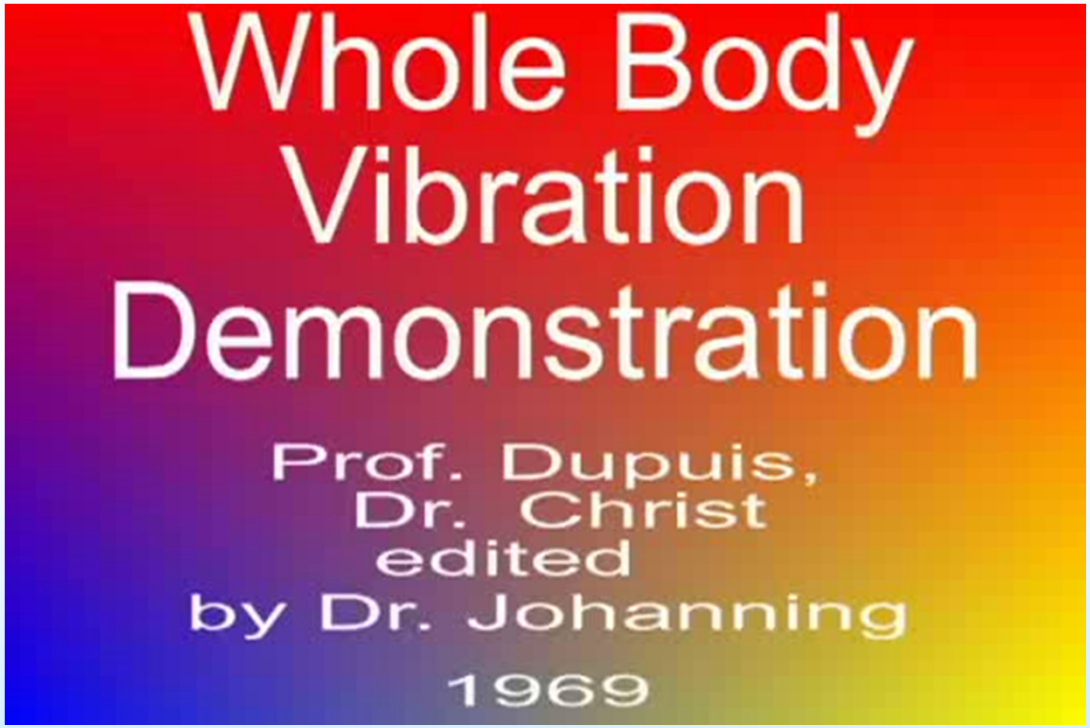


Taken from Brüel & Kjær document br056.pdf, "Primer: Human Vibration," http://www.bksv.co.uk/doc/br056.pdf

See also Brüel & Kjær document bn1330.pdf, "Mechanical Vibration and Shock Measurements," http://www.bksv.co.uk/doc/bn1330.pdf

Video of Resonance of Internal Organs Under Vertical Vibration.

http://www.youtube.com/watch?v=n5-BeQXC29Q



Old ISO Human Response Limits (IS0 2631-1:1985)

1. Measure acceleration in x-, y-, or z-direction.
2. Compute the r.m.s. acceleration in one-third octave bands with center frequencies of 1 Hz to 100 Hz (see the horizontal axis in the figure.
3. Find the allowable time of exposure from the chart.
4. The top line is for 1 minute exposure and the bottom line is for 24 hours.
5. The vertical scale is in m/s^2.
6. Time of exposure limits (or sensitivity to vibration) are functions of frequency. On average, people are most sensitive to vertical vibration between center frequencies of 4 to 8 Hz.

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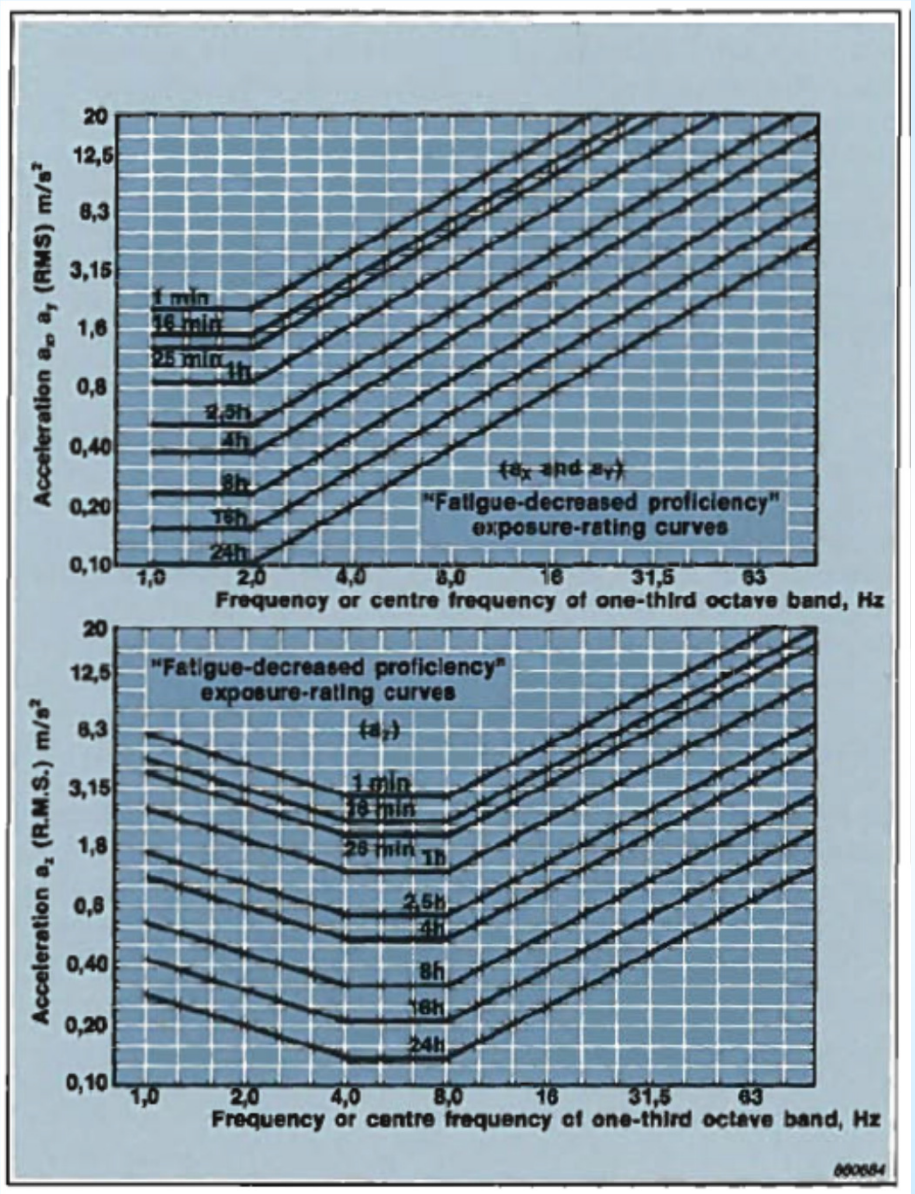


Latest ISO Human Response Limits (IS0 2631-1:1997)

- The procedure has been reversed:
  1. Apply a set of four weighting functions to normalize the measured acceleration signal to give a flat response with respect to human sensitivity to vibration.
  2. Compute the r.m.s. of the weighted acceleration signal.
  3. Compare the r.m.s. value with published criteria of correlations.

Importance of the New Procedure to Aircraft Response Analysis

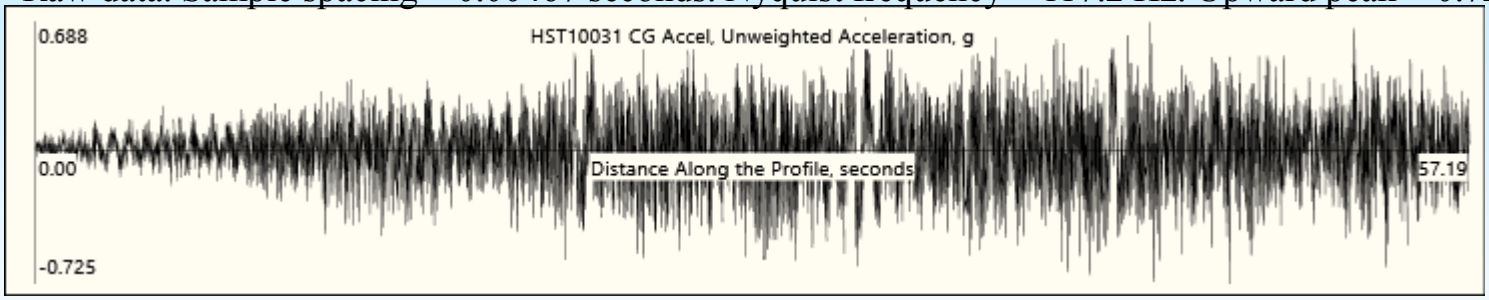
- A standardized procedure is available for processing an accelerometer signal before applying limit criteria.
- For example, peak accelerations in the range 0.3 to 0.4 g (gravity units, 1 g = 9.807 m/s^2) are frequently used as limit criteria for acceptable aircraft response to pavement roughness.
- But the data processing conditions are not usually specified or, even, reported.

Example of Measured Accelerations Processed to Different Bandwidths

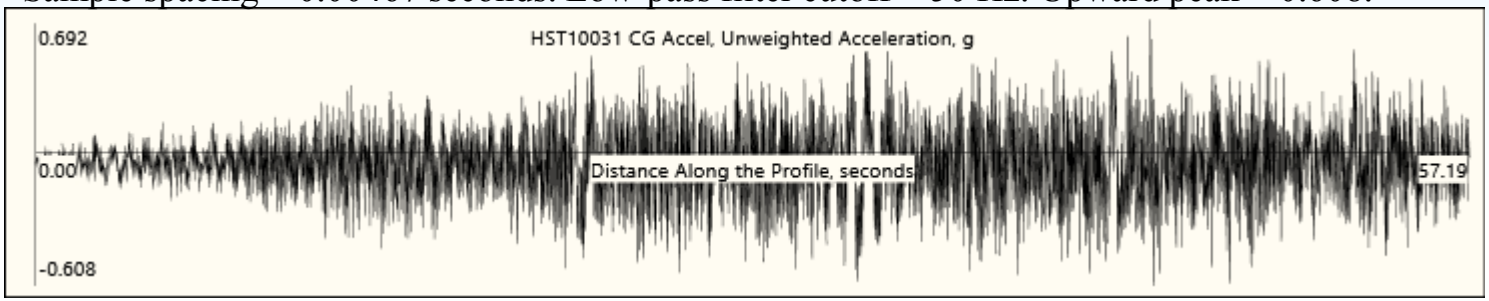
- Aircraft: FAA instrumented Boeing 727-100QC.
- Accelerometers at the CG and on the cockpit floor at the pilot's seat.

727-100QC CG Accelerations

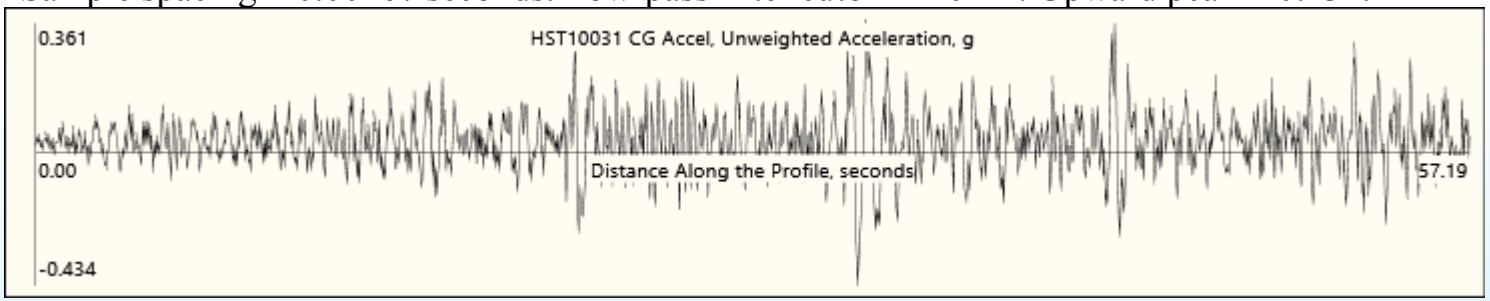
Raw data. Sample spacing = 0.00467 seconds. Nyquist frequency = 117.2 Hz. Upward peak = 0.725.



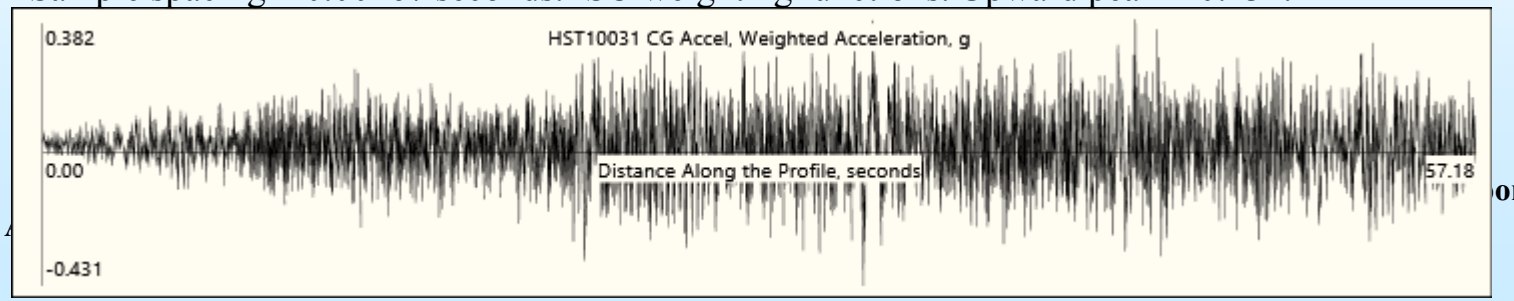
Sample spacing = 0.00467 seconds. Low-pass filter cutoff = 50 Hz. Upward peak = 0.608.



Sample spacing = 0.00467 seconds. Low-pass filter cutoff = 10 Hz. Upward peak = 0.434.



Sample spacing = 0.00467 seconds. ISO weighting functions. Upward peak = 0.431.



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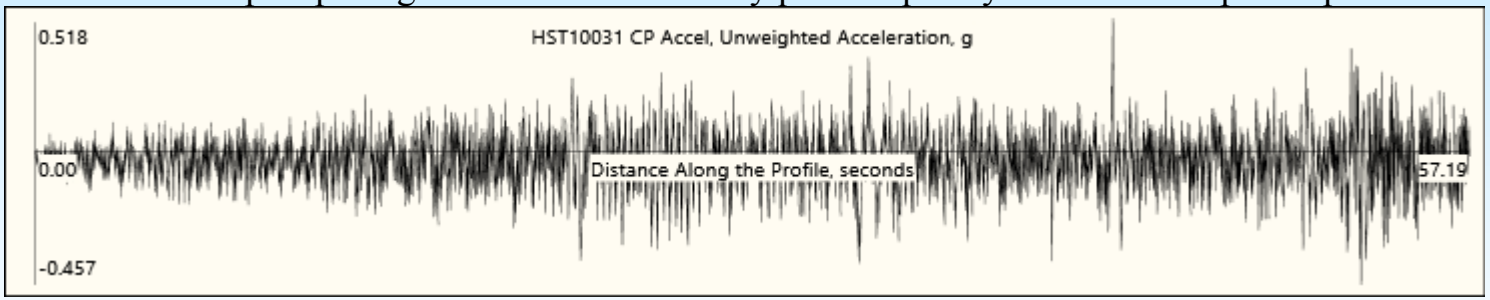
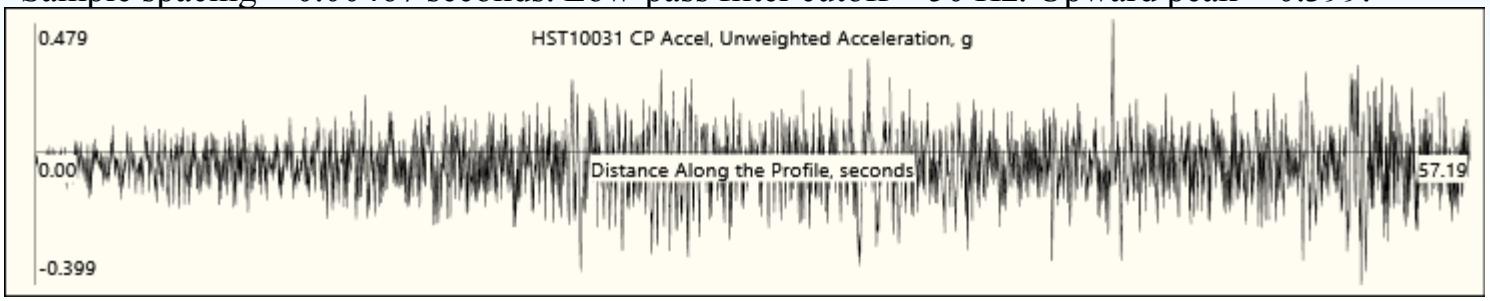
727-100QC Cockpit Accelerations

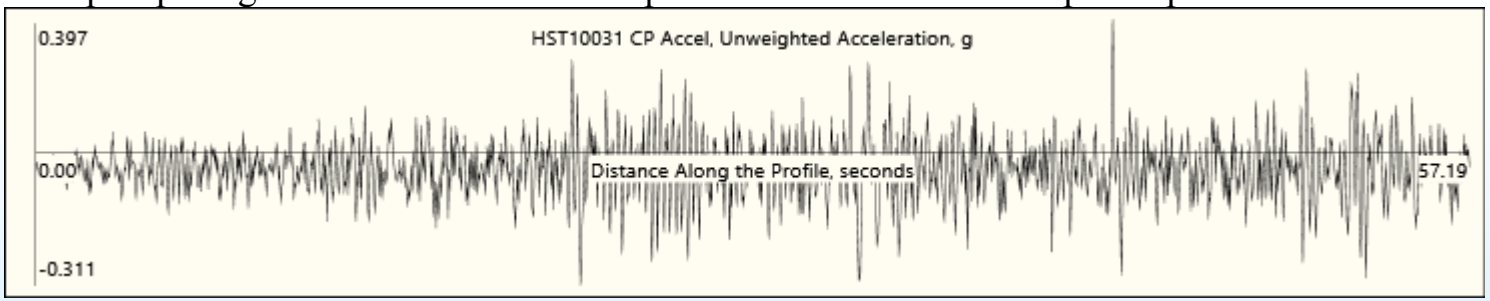
Raw data. Sample spacing = 0.00467 seconds. Nyquist frequency = 117.2 Hz. Upward peak = 0.457.



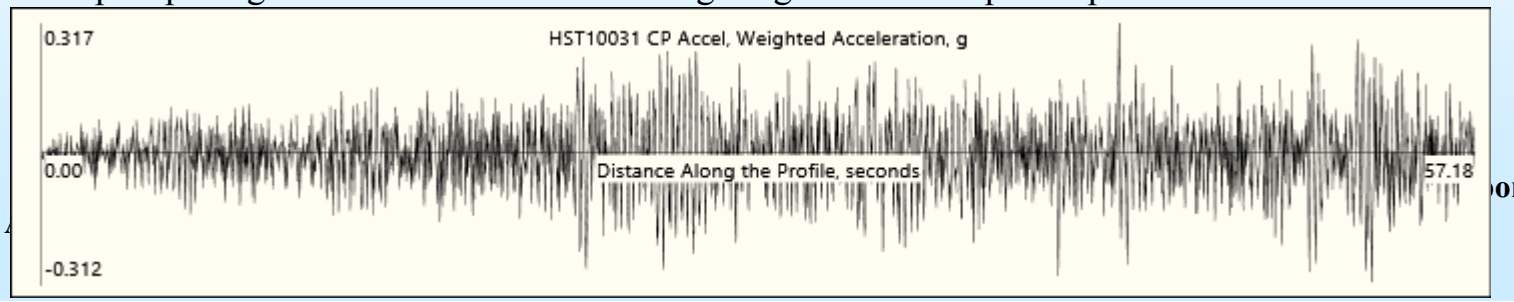
Sample spacing = 0.00467 seconds. Low-pass filter cutoff = 50 Hz. Upward peak = 0.399.



Sample spacing = 0.00467 seconds. Low-pass filter cutoff = 10 Hz. Upward peak = 0.0.311.



Sample spacing = 0.00467 seconds. ISO weighting functions. Upward peak = 0.312.



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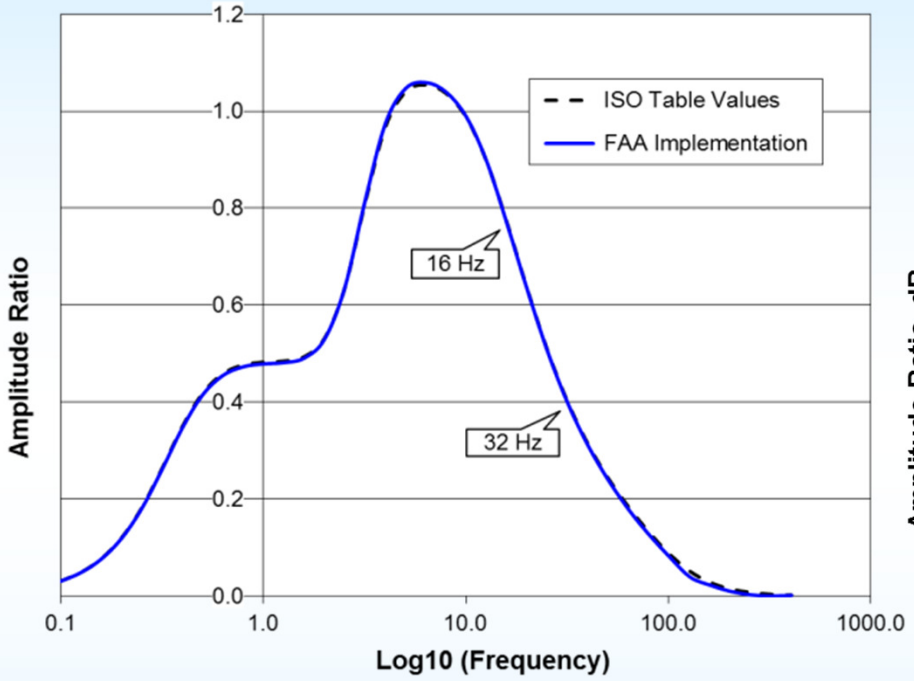
ISO 6321 Weighting Functions

- $|H_{\text{Overall}}(p)| = |H_l(p)| \,.\, |H_t(p)| \,.\, |H_h(p)| \,.\, |H_s(p)|$

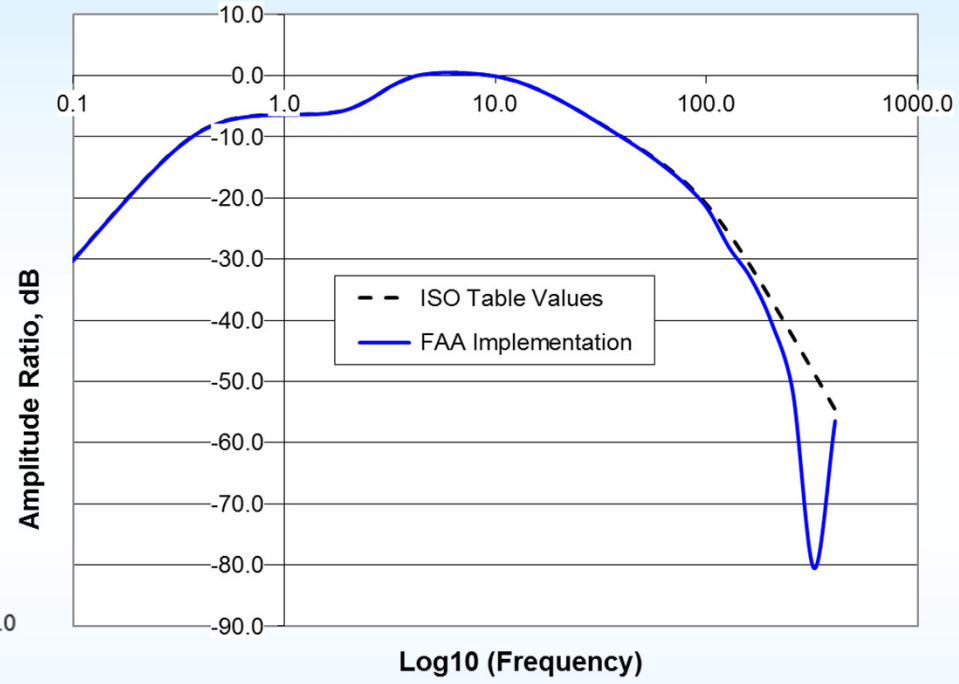
1. Low pass section, $|H_l(p)| = \left|\frac{1}{1 + \sqrt{2}\,p/\omega_2 + (p/\omega_2)^2}\right| = \sqrt{\frac{f_2^4}{f^4 + f_2^4}}$.
2. Acceleration-velocity transition, $|H_t(p)|$.
3. High pass section, $|H_h(p)|$.
4. Upward step, $|H_s(p)|$.

- Apply each of the filters by integrating the acceleration signal in the order above using a Runge-Kutta procedure.
- The weighting functions were originally implemented for use in the subjective pilot's rating study.

Transfer Function of $|H_{Overall}(f)|$



Absolute Amplitude Ratio



Amplitude Ratio in Decibels

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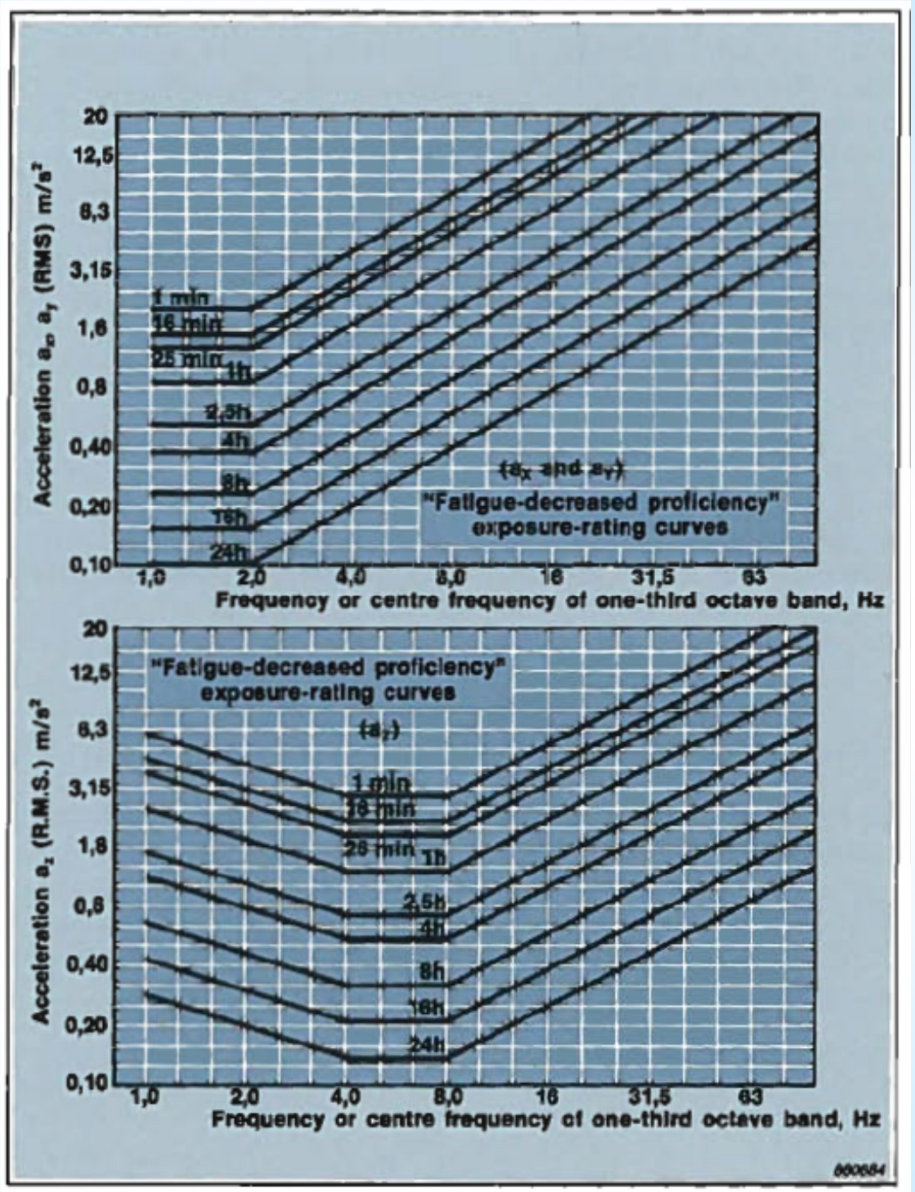


Discomfort Criteria in Annex C.2.3 of ISO 2631-1:1997

Weighted RMS, m/s^2	**Discomfort Level**
Less than 0.315	not uncomfortable
0.315 to 0.63	a little uncomfortable
0.5 to 1.0	fairly uncomfortable
0.8 to 1.6	uncomfortable
1.25 to 2.5	very uncomfortable
Greater than 2.0	extremely uncomfortable

Index Computations, Including Additional Indices for Shock

Index Name	Computation Formula
Weighted r.m.s.	$a_{\mathrm{W}} = \left[\frac{1}{T}\int_0^T a_{\mathrm{W}}^2(t)\,\mathrm{d}t\right]^{\frac{1}{2}}$
Running r.m.s. (τ = 1 second) MTVV = Maximum $a_W(t_0)$	$a_{\mathrm{W}}(t_0) = \left\{\frac{1}{\tau}\int_{t_0-\tau}^{t_0}\left[a_{\mathrm{W}}(t)\right]^2\,\mathrm{d}t\right\}^{\frac{1}{2}}$
Fourth Power Vibration Dose	$\mathrm{VDV} = \left\{\int_0^T\left[a_{\mathrm{W}}(t)\right]^4\,\mathrm{d}t\right\}^{\frac{1}{4}}$
Spinal Response Acceleration Dose	Neural Network

Note: See the standard for more details and instructions on how to apply the indices.

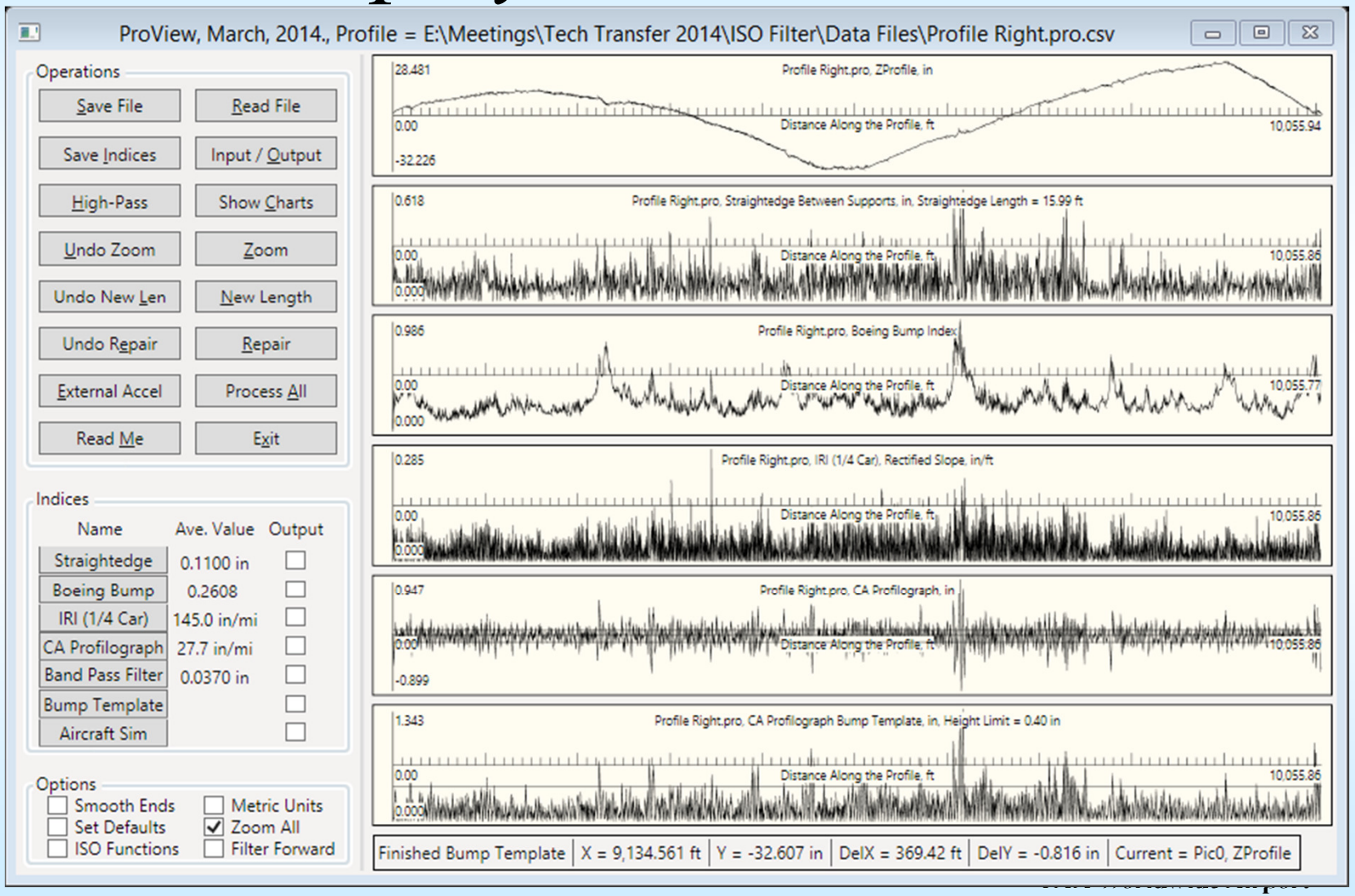
ProFAA

- ProFAA is the FAA's computer program for analyzing airport pavement longitudinal roughness profiles. It is written in VB6. Roughness index values can be computed for the following.
  - Physical straightedge.
  - Boeing Bump.
  - California Profilograph PI with Bump Template.
  - IRI (ASTM E1926-08).
  - Band-pass filter with r.m.s. output.
  - Aircraft simulations: 727, 747, DC9, DC-10.

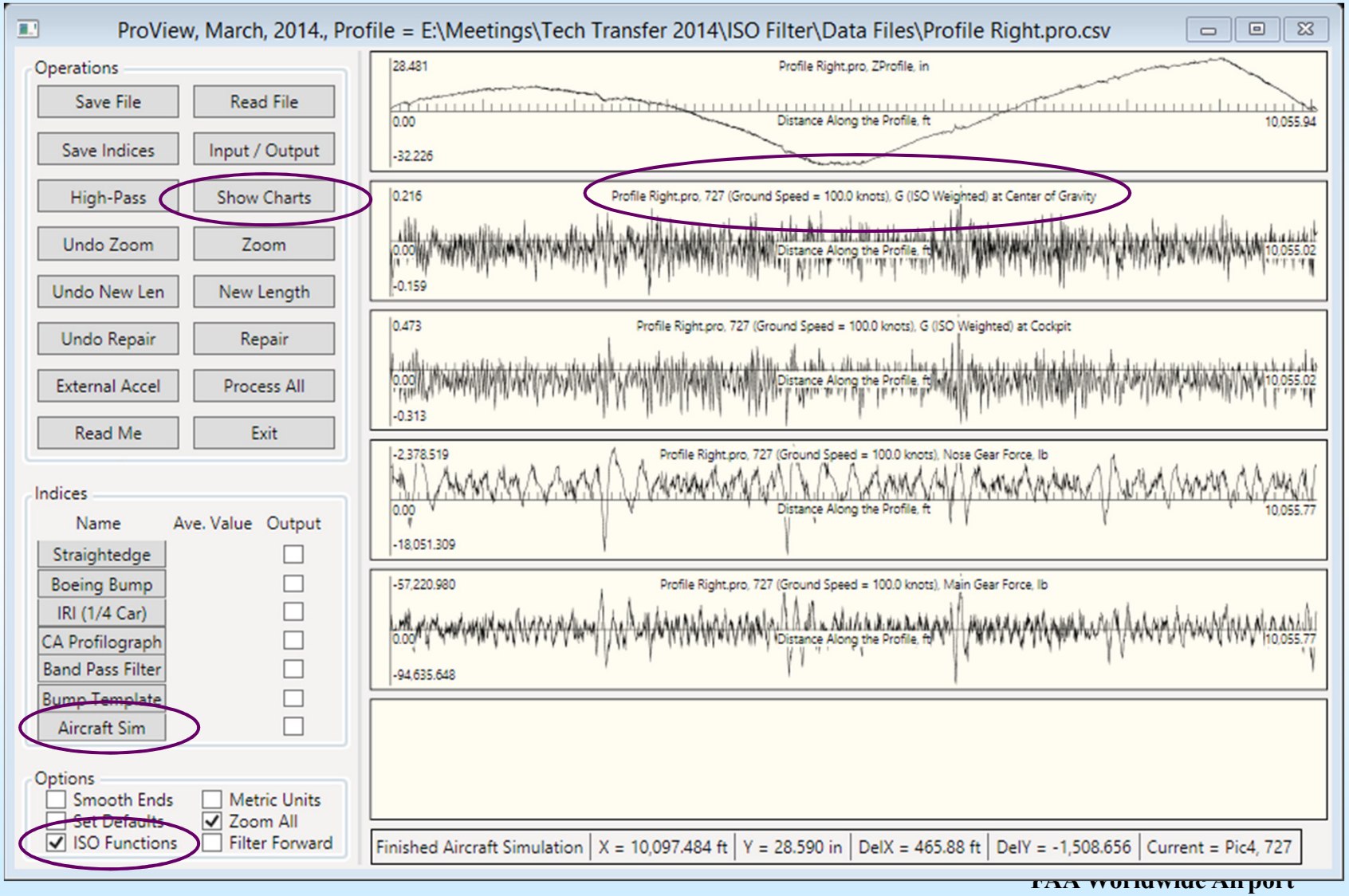
ProView

- ProView is a development of ProFAA and is written in VB.NET under the Windows Presentation Foundation (WPF) user interface system. Features which have been added include:
  - Three additional straightedge types.
  - Ride Number (ASTM E1489-08).
  - Adjustable band-width for the band-pass filter.
  - Accepts *.pro and *.csv profile files.
  - Reads external *.csv acceleration files.
  - Implements the ISO weighting functions for aircraft simulation accelerations and external accelerations.
  - Implements the ISO index computations.

ProView Screenshot Showing Index Displays



ProView Screenshot Showing Aircraft Simulation With ISO Weighted Accelerations



Output Text for Aircraft Simulation

```
Summary of Aircraft Response
Aircraft type = 727
Aircraft speed = 170.1 ft/s = 100.8 knots
Profile file = G:\Tech Transfer 2014\
 Profile Right.pro.csv
Profile total length = 10,055.8 ft
Profile decimated distance step length for
 simulation = 0.8202 ft
Simulation time step length = 0.004822 seconds
GroundNInner = 2
Simulation inner time step length
 = 0.002411 seconds

Center of gravity (Gcg) and cockpit (Gcp)
 accelerations, gravity units.
Gcg and Gcp are ISO weighted. They are summarized
 over the full length of the profile.
Location        Min         Max         RMS
   cg        -0.13573     0.18987     0.03361
 cockpit     -0.26376     0.38369     0.06775

Vertical landing gear forces, lb, summarized
 over the full length of the profile.
  Location         Min         Max       Average
    nose          -9,973      -3,470       5,863
    main         -85,401     -56,364      70,649
```

Aircraft responses summarized over each profile section.
Gcg and Gcp, gravity units, are ISO weighted.

Section No.	Length ft	Gcg RMS	Gcp RMS	Gcg Min	Gcp Min	Nose Ave, lb	Main Ave, lb
1	4,100	0.03327	0.06939	-0.13573	-0.26376	5,856	70,585
2	901	0.04152	0.06732	-0.12626	-0.22734	5,926	70,821
3	1,001	0.02867	0.05827	-0.08124	-0.21624	5,854	70,691
4	1,001	0.03891	0.08234	-0.09920	-0.24541	5,858	70,715
5	1,001	0.03596	0.06977	-0.11782	-0.20971	5,833	70,673
6	951	0.02594	0.04977	-0.06071	-0.15814	5,824	70,527
7	1,102	0.03007	0.06682	-0.09198	-0.20223	5,913	70,732

Weighted Gcg ISO Index values, m/s^2, computed over each profile section.

Section No.	Length ft	RMS	Crest Factor	MTVV	VDV	Spinal Dose
1	4,100	0.32626	4.07976	0.57782	3.58505	1.62909
2	901	0.40716	3.04101	0.57304	2.90921	1.69604
3	1,001	0.28102	3.18778	0.35447	2.07150	0.99735
4	1,001	0.38177	4.87743	0.69563	3.28579	1.26447
5	1,001	0.35267	3.27606	0.47461	2.62233	1.08225
6	951	0.25443	2.76350	0.32376	1.77851	0.77415
7	1,102	0.29406	3.37327	0.39164	2.16214	1.15868

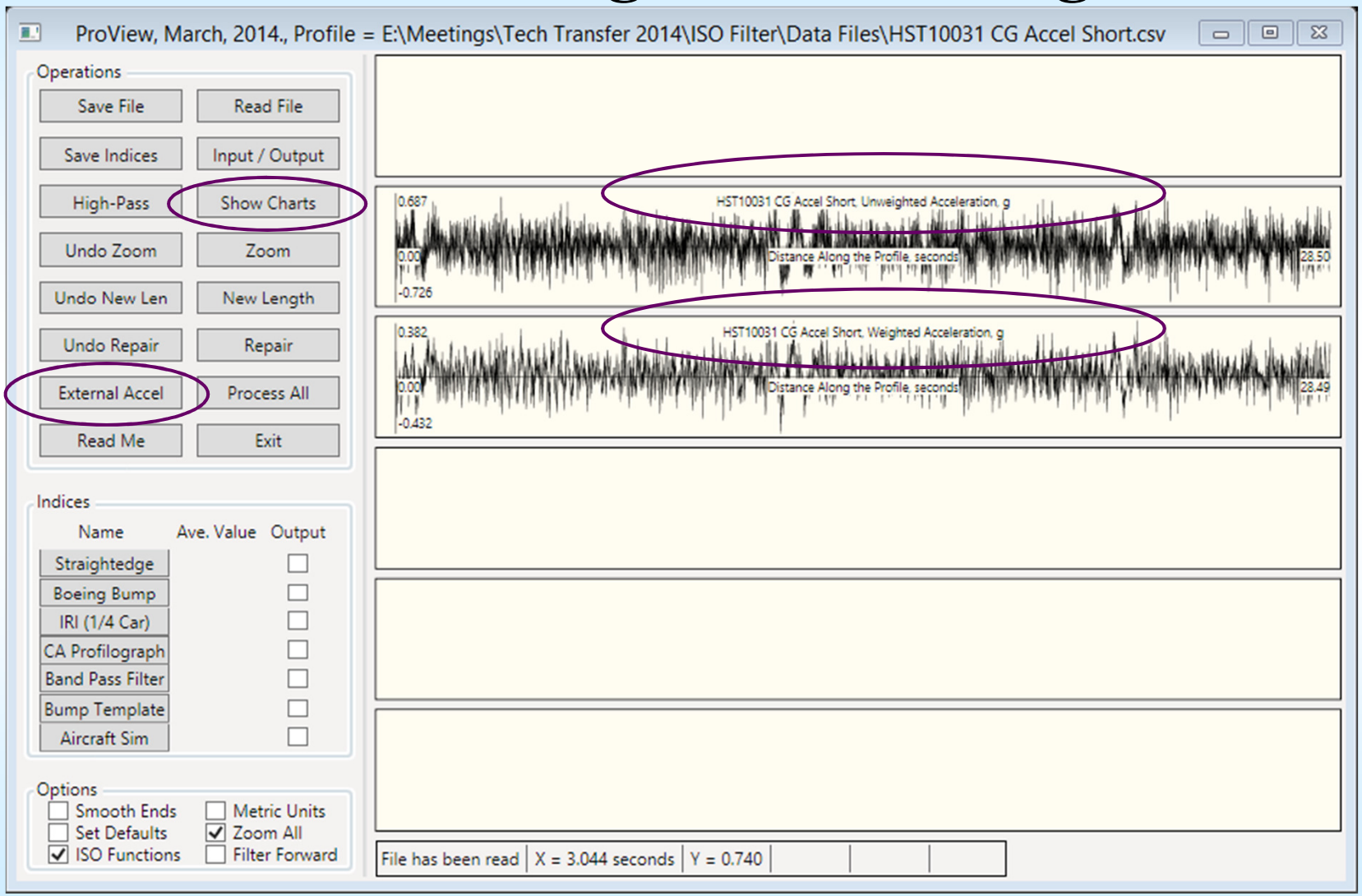
Weighted Gcp ISO Index values, m/s^2, computed over each profile section.

Section No.	Length ft	RMS	Crest Factor	MTVV	VDV	Spinal Dose
1	4,100	0.68050	3.80095	1.33736	7.49673	3.32203
2	901	0.66053	3.37522	0.91960	4.74002	2.29200
3	1,001	0.57181	3.70850	0.86700	4.43713	2.28635
4	1,001	0.80755	4.65939	1.56039	7.29391	2.36187
5	1,001	0.68437	3.00505	0.80138	4.99758	2.12137
6	951	0.48791	3.17854	0.64262	3.44902	1.63731
7	1,102	0.65515	3.02705	0.77552	4.66564	2.06620

ISO Index values, m/s^2, computed over the full length of the profile.

Location	RMS	Crest Factor	MTVV	VDV	Spinal Dose
cg	0.32960	5.64941	0.69563	4.60844	1.92944
cockpit	0.66440	5.66333	1.56039	9.49240	3.55373

ProView Screenshot Showing External Acceleration, Unweighted and Weighted



Output Text for External Acceleration

```
Summary of External Acceleration Data File Properties
Original accel data file    = G:\Tech Transfer 2014\HST10031 CG Accel Short.csv
Total length of record      = 28.5 seconds
Original record step length = 0.004267 seconds
Weighted record step length = 0.006250 seconds

ISO Weighted acceleration computed over the full length of the profile.
 Units       Min         Max         RMS
   g      -0.43201     0.38166     0.10740
 m/s^2    -4.23654     3.74285     1.05326

ISO Index values computed over the full length of the profile.
  Type     RMS    Crest Factor     MTVV        VDV     Spinal Dose
 Index   1.05326     4.02231     1.53650    11.45834     4.92287

External acceleration summarized over each profile section.
Section  Length     RMS     Average     Max
  No.   seconds      g         g         g
   1        5.3   0.12088  -0.00242   0.31773
   2        5.9   0.09850  -0.00077   0.32825
   3        5.9   0.11205  -0.00049   0.38114
   4        5.9   0.10787   0.00061   0.38166
   5        5.6   0.09610   0.00000   0.34822

Weighted acceleration ISO Index values, m/s^2, computed over each profile section.
Section  Length    RMS     Crest     MTVV     VDV    Spinal
  No.   seconds           Factor                     Dose
   1        5.3  1.18564  2.92801  1.30262  8.17041  3.84819
   2        5.9  0.96604  3.35132  1.13662  7.08449  3.07914
   3        5.9  1.09881  3.85557  1.53650  8.19554  4.37916
   4        5.9  1.05786  3.53813  1.37284  7.69574  3.46132
   5        5.6  0.94245  3.62345  1.14813  6.83341  3.13895
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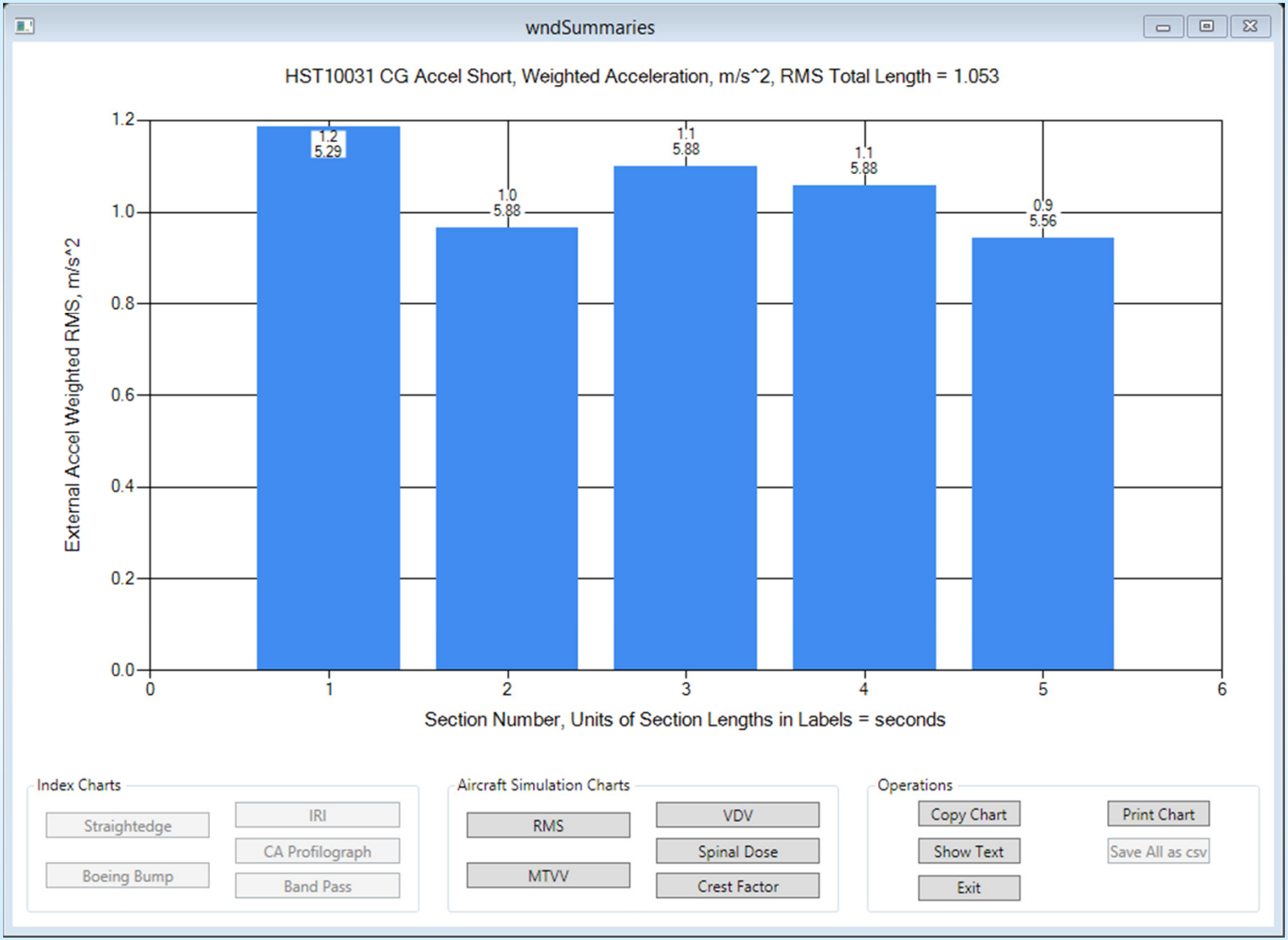
RMS Bar Chart From Show Charts



See the paper for more details on ProFAA and ProView and a comparison between the 727-100QC full-scale and simulation results.

Thank you for your attention.